

Possible Distance Indicators in Gamma-ray Pulsars

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Abstract Distance measurements of gamma-ray pulsars are challenging questions in present pulsar studies. The Large Area Telescope (LAT) aboard the Fermi gamma-ray observatory discovered more than 70 gamma-ray pulsars including 24 new gamma-selected pulsars which nearly have no distance information. We study the relation between gamma-ray emission efficiency ($\eta = L_\gamma/\dot{E}$) and pulsar parameters for young radio-selected gamma-ray pulsars with known distance information in the first gamma-ray pulsar catalog reported by Fermi/LAT. We have introduced three generation order parameters to describe gamma-ray emission properties of pulsars, and find the strong correlation of $\eta - \zeta_3$ a generation order parameter which reflects γ -ray photon generations in pair cascade processes induced by magnetic field absorption in pulsar magnetosphere. A good correlation of $\eta - B_{LC}$ the magnetic field at the light cylinder radius is also found. These correlations would be the distance indicators in gamma-ray pulsars to evaluate distances for gamma-selected pulsars. Distances of 25 gamma-selected pulsars are estimated, which could be tested by other distance measurement methods. Physical origin of the correlations may be also interesting for pulsar studies.

Key words: gamma rays: general – pulsars: general – stars: neutron

1 INTRODUCTION

Before 2008, only 7 gamma-ray pulsars are known in nature (Thompson 2001). The launch of the Fermi Gamma-ray Space Observatory in June 2008 completely changed the status in studies of gamma-ray pulsars. The first published catalog of gamma-ray pulsars (Abdo et al. 2010) contains 46 gamma-ray pulsars including 8 millisecond pulsars, 21 young radio pulsars and 17 gamma-selected pulsars. After more than one and half years of all-sky survey observations by Fermi/LAT, more than 70 gamma-ray pulsars were discovered, including 25 gamma-selected pulsars (see reviews by Ray & Saz Parkinson 2010). High sensitivity of the Fermi/LAT makes a new era for pulsar discoveries, specially for the population of radio-quiet gamma-ray pulsars.

The distance measurement of pulsars is always a difficult problem in pulsar studies. Trigonometric parallax measurements of radio pulsars are the reliable method, but are only available for the nearby pulsars (< 0.4 kpc) specially for a few radio millisecond pulsars (e.g. Lommen et al. 2006). The most common way to obtain radio pulsar distance is based on the computation from dispersion measurement (DM) coupled to an electron density distribution model like NE 2001 model (Cordes & Lazio 2002), which have been applied to most radio pulsars (e.g., Johnston et al. 1996; Keith et al. 2008). The pulsar distance can be also estimated from kinematic model: the distance of possible associated objects (supernova remnants, pulsar wind nebulae, star clusters, or HII regions) could be measured from Doppler shift of absorption or emission lines in HI spectrum together with the rotation curve model of the Galaxy (e.g., Robert et al. 1993; Camilo et al. 2006). The distance of some pulsars with X-ray emissions can be estimated from X-ray observations of the absorbing column (e.g. Romoni et al. 2005) or from correlations in X-ray luminosities versus spin-down power or photon index (Becker & Truemper 1997; Possenti et al. 2002; Gotthelf 2003; Wang 2009;

and references therein). These methods may be available for radio or even X-ray pulsars, but for gamma-selected pulsars if no possible associated objects, we would have no any information on their distance.

It is well known that X-ray luminosity has the correlation with pulsar's spin-down power: $L_x \propto \dot{E}$ in soft X-ray bands (0.1 – 2.4 keV, Becker & Truemper 1997), and $L_x \propto \dot{E}^{3/2}$ in hard X-ray bands (> 2 keV, see Saito 1998; Cheng et al. 2004; Wang 2009). Based on the EGRET pulsars, Thompson et al. (1999) found a possible correlation of $L_\gamma \propto \dot{E}^{1/2}$. For the larger sample of gamma-ray pulsars in Abdo et al. (2010), the young pulsars looks to still follow this relation with a large scattering factors of more than 10 but millisecond pulsars follow a different relation (see Fig. 6 of Abdo et al. 2010). This correlation was used to estimate some gamma-selected pulsars (Saz Parkinson et al. 2010). Moreover, the relation of $L_\gamma \propto \dot{E}^{1/2}$ may not be intrinsic, for the young gamma-ray pulsars in Fig. 6 of Abdo et al. (2010), we find a fitting function of $L_\gamma \propto \dot{E}^{0.7}$.

Gamma-ray emission efficiency ($\eta = L_\gamma/\dot{E}$) is an important parameter in gamma-ray pulsars, which varies for different populations of pulsars. In this paper we study the relations of gamma-ray emission efficiency versus some pulsar parameters: spin period, age, magnetic field at light cylinder, and three generation order parameters. We will show results of these relations and good correlations would be pulsar distance indicators for gamma-selected pulsars.

2 GAMMA-RAY EMISSION EFFICIENCY VERSUS PULSAR PARAMETERS

Gamma-ray emission efficiency is defined as $\eta = L_\gamma/\dot{E}$, where the spin-down power $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$ taking $I = 10^{45}$ g cm², P is the period of pulsar in units of second. $L_\gamma = 4\pi d^2 f_\Omega F_\gamma$, where F_γ is the gamma-ray flux above 100 MeV detected by Fermi/LAT. The radiation open angle factor f_Ω is model-dependent, and may depend on the magnetic inclination and observer angles, which could be obtained using pulse profile information (e.g., $f_\Omega \sim 1$ for 8 gamma-ray pulsars estimated by Watters et al. 2009). For simplicity, we use $f_\Omega = 1$ in this paper similar to Abdo et al. (2010). In the gamma-ray pulsar catalog given by Abdo et al. (2010), 21 radio-selected young pulsars and 7 gamma-selected pulsars have the distance measurements or estimation. However, gamma-ray emission efficiency of some gamma-selected pulsars are higher than 1, the maximum radiation efficiency in physics, suggesting overestimation of the distance for some gamma-selected pulsars. Millisecond pulsars may have different properties from young pulsars, so we do not consider 8 millisecond pulsars in the catalog here. Finally, we use these 21 radio-selected pulsars for the analysis in this section. The efficiency η distributes from 0.1% (like Crab pulsar) to near 100%.

We will first show the relations between η versus three well known pulsar parameters: P , τ and B_{LC} . Most importantly, we have introduced the generation order parameters for pulsars (see details in Wang & Zhao 2004 and therein references) which can be used to describe gamma-ray properties in pulsars. In §2.2, the relations between η versus three generation order parameters will be studied.

2.1 η versus P , τ and B_{LC}

In Fig. 1, we plot diagrams of η versus P , τ and B_{LC} for 21 young gamma-ray pulsars, respectively. $\tau = P/\dot{P}$ is the pulsar's characteristic age, $B_{LC} \sim 2.94 \times 10^8 (\dot{P} P^{-5})^{1/2}$ is the magnetic field at the light cylinder ($R_{LC} = cP/2\pi$).

In the diagram of $\eta - P$, the data points of spin period are scattering, no significant correlation is found. But η seems to have the correlations with the other two pulsar parameters: age and the magnetic field at the light cylinder. The linear function is used to fit the correlations (solid lines in Fig. 1):

$$\log \eta = -(4.73 \pm 0.31) + (0.68 \pm 0.08) \log \tau \quad (1)$$

with a standard deviation of $\sigma \sim 1.63$ and the probability value (p -value for t-test) of 1.09×10^{-4} ;

$$\log \eta = (2.23 \pm 0.32) - (0.88 \pm 0.10) \log B_{LC} \quad (2)$$

with $\sigma \sim 1.56$, and a p -value of 2.90×10^{-5} .

The gamma-ray efficiency generally become higher with older age and smaller B_{LC} . From the evaluation of the standard deviation values σ and p -values, the relation of $\eta - B_{LC}$ is the better one.

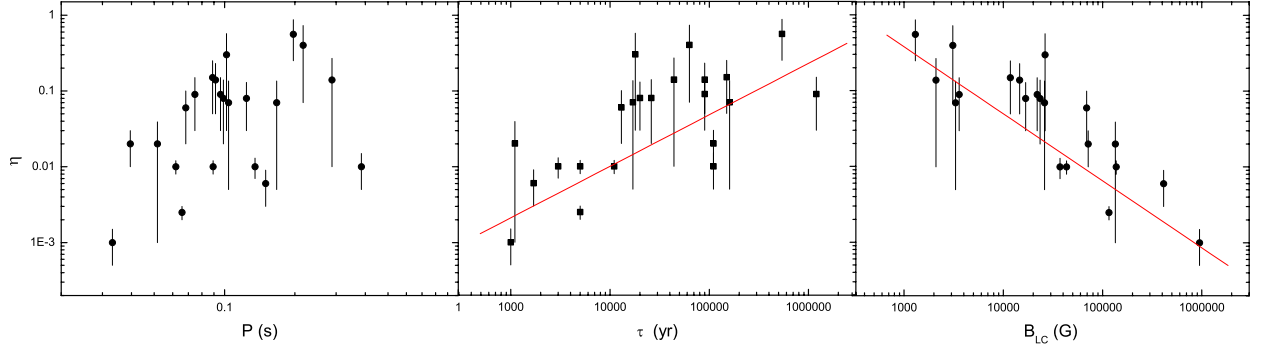


Fig. 1 Gamma-ray emission efficiency η of 21 young gamma-ray pulsars versus three pulsar parameters: spin period P , age τ and the magnetic field at light cylinder B_{LC} . η shows the correlations with two pulsar parameters τ and B_{LC} , and the solid lines display the best fitting functions. See the text for details.

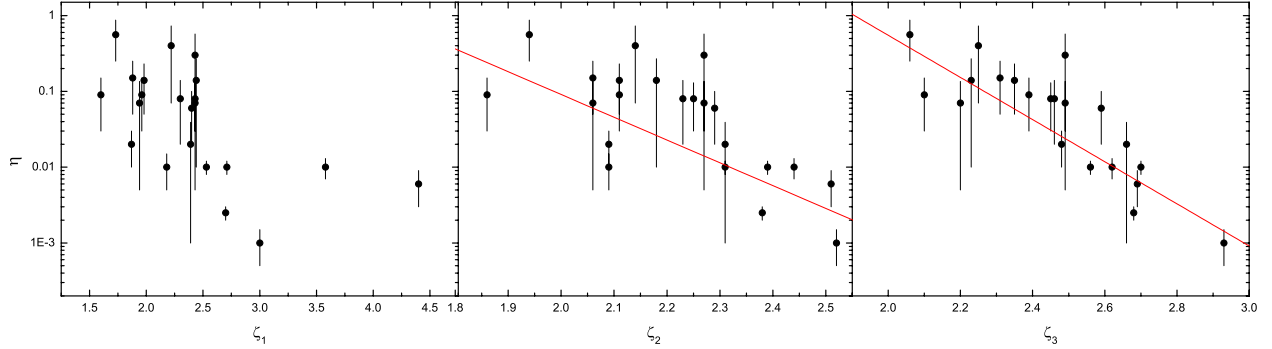


Fig. 2 Gamma-ray emission efficiency η of 21 young pulsars versus three generation order parameters ζ_{1-3} in gamma-ray pulsars. η has no significant correlation with ζ_1 but has the correlation with ζ_2 and ζ_3 , suggesting that the magnetic field dominates the gamma-ray absorption in cascade processes. The solid lines show the best fitting function. See the text for details.

2.2 η versus generation order parameters

The concept of generation is provided to describe pair cascade processes in gamma-ray pulsars (Zhao et al. 1989, Lu & Shi 1990). Based on Ruderman-Sutherland scenario (Ruderman & Sutherland 1975), passing through the polar gap, e^+/e^- are accelerated to a high energy with typical Lorentz factor $\gamma_1 = 6.0 \times 10^7 P^{1/14} \dot{P}_{15}^{-1/14}$, where \dot{P}_{15} the derivative in units of $10^{-15} \text{ s s}^{-1}$. These first generation particles will move along the curved magnetic field lines and emit high energy curvature radiation (the first generation photons) with photon energy typically at

$$E_1 = \frac{3}{2} \frac{\hbar c}{R_c} \gamma_1^3 \approx 3.2 \times 10^{10} P^{-2/7} \dot{P}_{15}^{-3/14} \text{ eV}, \quad (3)$$

where $R_c \approx 1.8 \times 10^7 P^{1/2} \text{cm}$ is the curvature radius of field line here. These primary photons could be converted into secondary e^+/e^- pairs in both open and closed magnetic field line regions near the neutron star surface due to magnetic pair creation (Halpern & Ruderman 1993). And the condition of these photons to create e^+/e^- pairs is (Sturrock 1971; Ruderman & Sutherland 1975)

$$\frac{E_1}{2m_e c^2} \frac{B(r_s)}{B_c} \approx \frac{1}{15}, \quad (4)$$

where $B(r_s)$ is the local magnetic field at the position of r_s , and $B_c = m_e^2 c^3 / e \hbar = 4.14 \times 10^{13} \text{ G}$ is the critical magnetic field. These e^+/e^- can emit the second generation photons through synchrotron radiation with a characteristic energy E_2 . If E_2 is high enough, the further e^+/e^- pairs (the third generation) can be produced under the condition similar to Eq. (4),

$$\frac{E_2}{2m_e c^2} \frac{B(r_s)}{B_c} \approx \frac{\chi_0}{15}, \quad (5)$$

where $\chi_0/15 \sim 1/9 - 1/12$ (Sturrock 1971). Then pair cascade processes occur.

Concerning this idea, Lu et al. (1994) introduced the generation order parameter (GOP) to characterize a pulsar. They considered the conversion of high energy photons into e^+/e^- pairs through electric fields, and defined the first GOP as

$$\zeta_1 = 1 + \frac{1 - (11/7)\log P + (4/7)\log \dot{P}_{15}}{3.56 - \log P - \log \dot{P}_{15}}. \quad (6)$$

Wei et al. (1997) considered absorption of high energy photons by the effect of both magnetic and electric fields, define the second GOP as,

$$\zeta_2 = 1 + \frac{0.8 - (2/7)\log P + (2/7)\log \dot{P}_{15}}{1.3}. \quad (7)$$

The concept of generation was initially considered in the scheme that the γ -ray photons is absorbed and converted into e^+/e^- through only magnetic fields (Zhao et al. 1989), so we defined the third GOP based on the magnetic field absorption effects as (Wang & Zhao 2004)

$$\zeta_3 = 1 + \frac{0.6 - (11/14)\log P + (2/7)\log \dot{P}_{15}}{1.3}. \quad (8)$$

GOPs are used to describe cascade processes and characterize the spectral properties of pulsars. If a pulsar can emit gamma-rays, the GOPs must be larger than 1 (i.e., the first generation gamma-ray photons must exist). In addition, the GOPs are proved to be correlated with the gamma-ray photon index: softer gamma-ray photons with larger GOPs based on the EGRET pulsar sample (Lu et al. 1994; Wei et al. 1997). Then according to the definition of GOPs, the first generation pairs emit high energy gamma-rays (i.e., $> 100 \text{ MeV}$), with larger GOPs, more first generation pairs are transferred into next generation pairs with lower energy which emit more soft gamma-rays and X-rays. So given a total emission rate, efficiency to GeV gamma-rays (η) becomes lower with larger GOPs.

In Fig. 2, we plot the diagrams of η versus three GOPs (ζ_{1-3}) respectively. η has no correlation with ζ_1 but has correlation with other two GOPs ζ_2, ζ_3 , implying that magnetic fields dominate the absorption in pair cascade processes, consistent with our previous results (Wang & Zhao 2004). These correlations also suggest that GOPs (ζ_2, ζ_3) can describe gamma-ray properties of pulsars. In Fig. 2, the solid lines show the best fitting functions for the relations of $\eta - \zeta_2$ and $\eta - \zeta_3$:

$$\log \eta = (4.98 \pm 0.45) - (3.00 \pm 0.21)\zeta_2 \quad (9)$$

with $\sigma \sim 1.69$ and a p -value of 1.94×10^{-4} ;

$$\log \eta = (5.49 \pm 0.24) - (2.86 \pm 0.11)\zeta_3 \quad (10)$$

with $\sigma \sim 1.34$ and a p -value of 1.01×10^{-6} . The correlation between $\eta - \zeta_3$ is stronger with the smaller standard deviation and p -value.

Table 1 The estimated distances of 25 gamma-selected pulsars. d_{1-2} denotes the distance range calculated from relations of $\eta - \zeta_3$ and $\eta - B_{\text{LC}}$, respectively. d_3 is the estimated distance from other methods with references provided.

Pulsar	P s	\dot{P} s s ⁻¹	$F_\gamma (> 100 \text{ MeV})$ erg cm ⁻² s ⁻¹	d_1 kpc	d_2 kpc	d_3 kpc	reference
J0007+7303	0.316	3.61×10^{-13}	3.82×10^{-10}	$0.86^{+0.30}_{-0.32}$	$1.18^{+0.72}_{-0.44}$	1.4 ± 0.3	Pineault et al. 1993
J0357+32	0.444	1.20×10^{-14}	6.38×10^{-11}	$0.72^{+0.25}_{-0.29}$	$0.73^{+0.51}_{-0.30}$		
J0633+0632	0.297	7.95×10^{-14}	8.00×10^{-11}	$1.26^{+0.41}_{-0.48}$	$1.37^{+0.76}_{-0.60}$		
J0633+1746	0.237	1.10×10^{-14}	3.38×10^{-9}	$0.19^{+0.07}_{-0.07}$	$0.17^{+0.09}_{-0.06}$	$0.25^{+0.12}_{-0.06}$	Faherty et al. 2007
J1418-5819	0.111	1.70×10^{-13}	2.35×10^{-10}	$1.39^{+0.58}_{-0.57}$	$1.86^{+1.09}_{-0.80}$	2-5	Ng et al. 2005
J1459-60	0.103	2.55×10^{-14}	1.06×10^{-10}	$1.76^{+0.70}_{-0.67}$	$1.62^{+0.97}_{-0.69}$		
J1732-31	0.197	2.62×10^{-14}	2.42×10^{-10}	$0.77^{+0.41}_{-0.35}$	$0.86^{+0.49}_{-0.30}$		
J1741-2054	0.414	1.69×10^{-14}	1.28×10^{-10}	$0.59^{+0.26}_{-0.25}$	$0.80^{+0.48}_{-0.29}$	0.38 ± 0.11	Camilo et al. 2009
J1809-2332	0.147	3.44×10^{-14}	4.13×10^{-10}	$0.78^{+0.31}_{-0.31}$	$0.81^{+0.48}_{-0.30}$	1.7 ± 1.0	Oka et al. 1999
J1813-1246	0.048	1.76×10^{-14}	1.69×10^{-10}	$2.18^{+0.71}_{-0.64}$	$1.56^{+1.21}_{-0.68}$		
J1826-1256	0.110	1.21×10^{-13}	3.34×10^{-10}	$1.29^{+0.56}_{-0.44}$	$1.39^{+0.86}_{-0.60}$		
J1836+5925	0.173	1.49×10^{-15}	5.99×10^{-10}	$0.32^{+0.13}_{-0.14}$	$0.27^{+0.15}_{-0.09}$	< 0.8	Halpern et al. 2007
J1907+0602	0.107	8.68×10^{-14}	2.75×10^{-10}	$1.39^{+0.46}_{-0.40}$	$1.42^{+0.95}_{-0.61}$		
J1958+2846	0.290	2.10×10^{-13}	8.45×10^{-11}	$1.54^{+0.56}_{-0.51}$	$1.86^{+1.01}_{-0.78}$		
J2021+4026	0.265	5.48×10^{-14}	9.76×10^{-10}	$0.38^{+0.20}_{-0.21}$	$0.46^{+0.20}_{-0.18}$	1.5 ± 0.5	Landecker et al. 1980
J2032+4127	0.143	1.98×10^{-14}	1.11×10^{-10}	$1.32^{+0.49}_{-0.52}$	$1.33^{+0.71}_{-0.50}$	$1.6 - 3.6$	Camilo et al. 2009
J2238+59	0.163	9.86×10^{-14}	5.44×10^{-11}	$2.36^{+0.75}_{-0.70}$	$2.64^{+1.36}_{-0.93}$		
J1023-5746	0.111	3.84×10^{-13}	2.69×10^{-10}	$1.77^{+0.70}_{-0.55}$	$2.09^{+0.95}_{-0.88}$		
J1044-5737	0.139	5.46×10^{-14}	1.03×10^{-10}	$1.72^{+0.60}_{-0.65}$	$1.86^{+0.86}_{-0.72}$		
J1413-6205	0.110	2.78×10^{-14}	1.29×10^{-10}	$2.52^{+0.89}_{-0.92}$	$1.56^{+1.12}_{-0.60}$		
J1429-5911	0.116	3.05×10^{-14}	9.26×10^{-11}	$1.84^{+0.64}_{-0.69}$	$1.79^{+0.97}_{-0.70}$		
J1846+0919	0.226	9.92×10^{-15}	3.58×10^{-11}	$1.52^{+0.55}_{-0.70}$	$1.44^{+0.80}_{-0.51}$		
J1954+2836	0.093	2.12×10^{-14}	9.75×10^{-11}	$1.90^{+0.67}_{-0.80}$	$1.72^{+1.10}_{-0.71}$		
J1957+5033	0.375	7.08×10^{-15}	2.27×10^{-11}	$1.22^{+0.41}_{-0.45}$	$1.31^{+0.65}_{-0.37}$		
J2055+2500	0.320	4.08×10^{-15}	1.15×10^{-10}	$0.56^{+0.19}_{-0.23}$	$0.61^{+0.30}_{-0.19}$		

3 POSSIBLE DISTANCE INDICATORS FOR GAMMA-RAY SELECTED PULSARS

In §2, the relations between η and six pulsar parameters: P , τ , B_{LC} and three GOPs ζ_1 , ζ_2 , ζ_3 are studied. From the values of standard deviation and p -values after fittings, the correlations of $\eta - \zeta_3$ is stronger than others, and the correlation of $\eta - B_{\text{LC}}$ could also be acceptable. In this paper we do not consider the physical origin in these correlations. These pulsar parameters can be estimated by two fundamental measurement parameters P and \dot{P} which are relatively easily observed. The gamma-ray emission efficiency is sensitively dependent on distance measurement which is very difficult at present, specially nearly impossible for gamma-selected pulsars. With the strong correlation of $\eta - \zeta_3$, we have a possible way to estimate a reliable distance for gamma-ray pulsars with only known P , \dot{P} and F_γ .

In the catalog of Abdo et al. (2010), 17 gamma-selected pulsars are listed and most of them have no any distance information. Saz Parkinson et al. (2010) claimed detections of 8 new gamma-selected pulsars in blind frequency searches of Fermi LAT data. In Table 1, we use the distance indicator obtained by $\eta - \zeta_3$ correlation to estimate the distances of the 25 gamma-selected pulsars. For comparison, we also give the predicted distance values calculated using the relation of $\eta - B_{\text{LC}}$. From Table 1, we find the evaluated distances (d_1 , d_2) by $\eta - \zeta_3$ and $\eta - B_{\text{LC}}$ correlations are similar, suggesting that these two distance indicators can be checked by each other.

In Table 1, we also collected the distance information (d_3) for some gamma-selected pulsars from other measurements or estimations. For the Geminga pulsar, we estimate the distance of 0.19 ± 0.07 kpc which is well consistent with the distance value of $0.25^{+0.12}_{-0.06}$ kpc from the optical trigonometric parallax measurement (Faherty et al. 2007). For PSR J1836+5925, we estimate its distance as ~ 0.3 kpc (corresponding to an efficiency of $\sim 55\%$) which is also well below the upper limits of 0.8 kpc according to its thermal X-ray spectrum (Halpern et al. 2007). For other gamma-selected pulsars, our estimated distance values are generally below those from other methods, but may be more reliable. According to the distance estimated

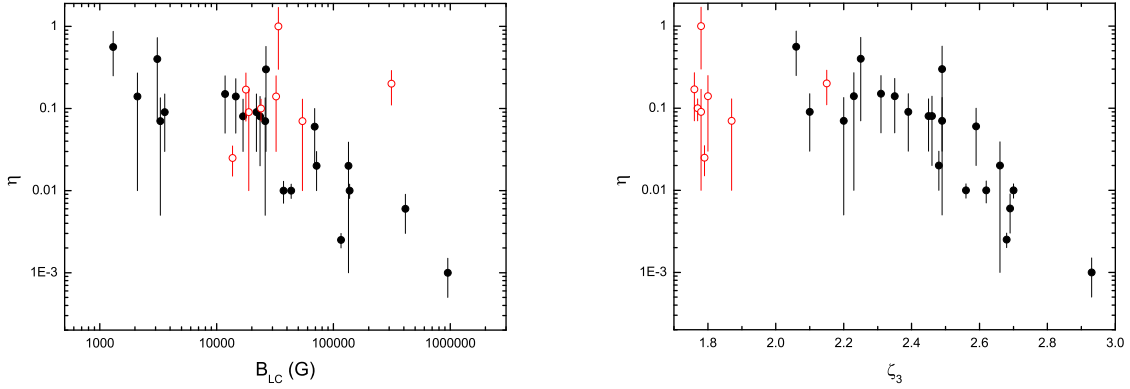


Fig. 3 Gamma-ray emission efficiency η versus B_{LC} and ζ_3 for both 21 young gamma-ray pulsars (solid circles) and 8 millisecond gamma-ray pulsars (open circles). Millisecond pulsars still generally follow the relations of $\eta - B_{LC}$ and $\eta - \zeta_3$ in young pulsars, but they may have a nearly constant gamma-ray radiation efficiency of $\eta \sim 10\%$.

from the $\eta - \zeta_3$ relation, the gamma-ray efficiency η is general below 1. The estimated efficiency of PSR J2021+4026 is about ~ 0.16 (corresponding to $d \sim 0.4$ kpc) according to the $\eta - \zeta_3$ relation, compared to $\eta \sim 0.9 - 3.6$ (corresponding to distance of 1 – 2 kpc) from kinematic model method on the possible association (Landecker et al. 1980).

4 SUMMARY AND DISCUSSION

In this article, we studied the possible correlations between gamma-ray emission efficiency η and 6 pulsar parameters: P , τ , B_{LC} and three generation order parameters ζ_{1-3} using 21 young radio-selected gamma-ray pulsars in Abdo et al. (2010). We find the strong correlation between $\eta - \zeta_3$. Based on the concept of the GOPs, larger GOPs imply that more high energy photons are transferred to softer photons (X-rays). The good correlation of $\eta - \zeta_3$ suggests that GOPs can describe gamma-ray emission properties of young pulsars, and the magnetic field absorption effects dominate in pair cascade processes in pulsar magnetosphere. This intrinsic correlation can be used to estimate distances for gamma-selected pulsars which have no any distance information yet. The good correlation of $\eta - B_{LC}$ is also found, which can be also used as the other distance indicator in gamma-ray pulsars for a double check.

Millisecond pulsars (MSPs) have not be included in our analysis, though their distances are generally measured by optical trigonometric parallax and DM methods. MSPs with much smaller P and \dot{P} have a much older characteristic age ($\tau \sim 10^9$ yr). The values of ζ_1 and ζ_2 are below 1 or near 1, making MSPs as non-gamma pulsars if these two GOPs are still applicable to MSPs. However, in parameter spaces of B_{LC} and ζ_3 , MSPs are similar to young pulsars. In Fig. 3, we plot the diagrams of $\eta - B_{LC}$ and $\eta - \zeta_3$ including both 21 young pulsars and 8 MSPs in the first gamma-ray pulsar catalog (Abdo et al. 2010). MSPs seems to still follow the behaviors of young pulsars: higher efficiency with smaller values of B_{LC} and ζ_3 . In the same time, gamma-ray emission efficiency of MSPs could also be thought to keep constant $\eta \sim 10\%$ (also see Fig. 6 of Abdo et al. 2010). So MSPs may have different gamma-ray emission properties from young pulsars, like multi-pole magnetic field assumption in MSPs (Ruderman 1991; Zhang & Cheng 2003), or different emission open angles (taken as $f_\Omega \sim 0.5$, Fierro et al. 1995). Present discoveries of MSPs are generally done through radio timing, and the blind search for MSPs by Fermi/LAT is a very important project in future, but quite difficult at present specially for MSPs in binaries. Then the distance

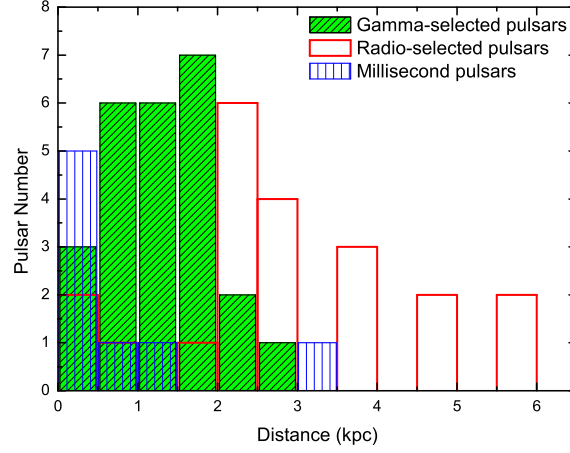


Fig. 4 The distance distributions of three classes of gamma-ray pulsars: gamma-selected pulsars, radio-selected pulsars and millisecond pulsars. The distances of gamma-selected pulsars are taken from the column d_1 of Table 1 according to the distance indicator of the $\eta - \zeta_3$ correlation.

indicators of $\eta - B_{LC}$ and $\eta - \zeta_3$ relations could be the secondary way for distance information of MSPs after trigonometric parallax or DM methods.

The GOP model was originally proposed based on the polar-cap accelerator scenario. The present Fermi/LAT may support that gamma-ray emission in pulsars mainly comes from the spatially extended regions reaching a good fraction of the light-cylinder radius (e.g., Abdo et al. 2010). The production of the secondary pairs in polar-cap activity is also different from that in the scenarios of outer-gap models or slot-gap models (e.g., Cheng, K. S. et al. 2000; Muslimov & Harding 2004). Then the new model of generation order parameters may be developed in the extended regions from the polar-cap regions to near the light-cylinder radius. This GOP model would be more complicated but could be considered in the next work. Anyway, the correlations of $\eta - \zeta_3$, $\eta - B_{LC}$ for gamma-ray pulsars suggest that the gamma-ray luminosity may depend on two fundamental pulsar parameters P and \dot{P} . The function of P and \dot{P} could well predict gamma-ray emission luminosity, which can be used to trace the distance of gamma-ray pulsars.

Fig. 4 shows the distance distributions of three classes of gamma-ray pulsars: gamma-selected pulsars, radio-selected pulsars and millisecond pulsars. The distances of gamma-selected pulsars are provided by the distance indicator of the $\eta - \zeta_3$ relation (see Table 1). Gamma-ray loud millisecond pulsars distribute at a distance peak around 0.3 kpc because MSPs generally have lower spin-down powers. Gamma-selected young pulsars distribute at the distance peak of ~ 1.2 kpc, while radio-selected young pulsars distribute at the distance peak of ~ 2.5 kpc. This difference in distance distributions for two classes of gamma-ray young pulsars may involve further interest. The nearby unresolved radio-quiet gamma-ray pulsars could contribute to diffuse gamma-ray background specially for the high-latitude pulsars located in the Gould Belt (Wang et al. 2005).

Before the Fermi era, only one gamma-selected pulsar Geminga was known. Now 25 gamma-selected pulsars are discovered, greatly improving our knowledge of gamma-ray pulsar family. Much more gamma-selected pulsars would be detected by future deeper sky surveys of Fermi/LAT. The distance indicators presented in this paper will give the distance information for gamma-selected pulsars, which will be helpful for study in gamma-ray emission properties of this pulsar population. It is still hopefully expected that more gamma-ray pulsars (young) have trigonometric parallax measurements or more precise DM model, which

can check the validity of the distance indicators (i.e., $\eta - \zeta_3$, $\eta - B_{LC}$), and improve the distance indicators in gamma-ray pulsars.

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